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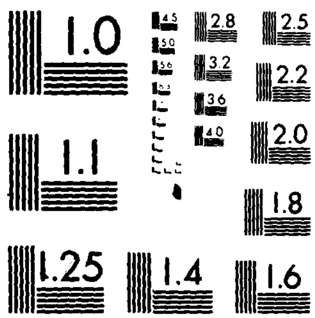

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NAVAL POSTGRADUATE SCHOOL
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THESIS

FEATURE ANALYSIS OF COMPUTER AIDED DESIGN

by

Daniel J. Devescovi

December 1981

Thesis Advisor: Norman R. Lyons

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Feature Analysis of Computer Aided Design

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN INFORMATION SYSTEMS

from the

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December 1981

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ABSTRACT

Computers in the architectural and engineering field have been used for many years. Recently, computers have been playing an increasing role in the design process itself through the development of computer aided design systems. The development of interactive computer graphics was a major contributor to the acceptance of the computer in assisting in the design process by the architectural and engineering community.

The emphasis is placed on the aspects of computer graphics interactive input devices, the requirement of complete geometric representation of objects and the corresponding data management problem. Computer aided design problems in reference to architectural and engineering design theory is discussed and a brief history of computer aided design with an overview of various systems is presented.

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I. INTRODUCTION TO COMPUTER AIDED DESIGN

The 1981, third edition of the "Computer Dictionary" defines computer aided design as [1]:

> A system by means of which engineers create a design and see the proposed product in front of them on a graphics screen or in a computer printout. With the computer, the proposed product can be analyzed for stress, vibration, heat, and other factors, and checked against government and industry standards.

This definition seems to give computer aided design a definite flavor of active participation by the computer in the creation of a design as a deliverable object made up of blueprints and specifications. Such a view stems from Sutherland's "SKETCHPAD" paper. He was the first to show that man could interact with computing machines by methods more direct than bits, numbers or punch cards. Computer aided design moved from the realm of analysis to the realm of a true assistant to the engineers and managers charged with the development of a new product in its final conceptual state. Designers have now a tool which gives them the potential of becoming more creative while still being able to be productive and efficient in their efforts.

The real challenge is to develop a computer aided design system which the designer, as user would accept in place of a paper sketch pad and pencil, a system which is both user

friendly and responsive to his perceived needs. It is the writer's intention to focus on these two areas in particular and to review the present status of the computer aided design systems as they pertain to the architectural and engineering efforts of the construction industry. The ability to interact in a visual mode with the computer through the use of a graphics terminal and the theory of design as applicable to computer aided design work will be discussed in chapters two and three. The turnkey computer aided design systems will be treated separately in chapter four. Turnkey systems were choosen for a more extensive discussion since they were developed solely to support computer aided design and appear to be the computer industry's answer to fulfill the architect and engineer's needs.

A brief history of computer aided design and a superficial examination of other systems available today is presented to give the reader an appreciation of the discussion which follows in subsequent chapters.

A. HISTORICAL BACKGROUND

In the late 1950's, efforts to automate manual design was already underway in the automotive, aerospace and ship building industries with the assistance of numerical control

programming languages. The development of computer graphics as an element of computer aided design in the early 1960's, gave an impetus to the potential to be derived from computers in the design process which is still felt today. Computer graphics was available previously, however, it was not until Sutherland's "SKETCHPAD" and the work done by the staff of the research laboratories of General Motors [2] that computer graphics was being considered almost synonymous with computer aided design. Both efforts utilized large machines with specially built display hardware.

By 1965 many people were attracted by the intriguing possibilities of computer graphics. The efforts to put together a computer graphics system around a small computer and associated software began to mount. Computer hardware and software development costs were still too high and the benefits of high volume production could not be realized, although augmenting computers with graphics was recognized to provide a tremendous increase in the potential application of computers.

Fortunately, however, at about the same time the cost of hardware decreased; newer and cheaper devices, some of limited capability, appeared on the market. General purpose

computing systems changed, they were no longer quite so inhospitable to the needs of graphic devices and their users. By 1970, the first stand alone interactive graphic systems became commercially available and a new "turnkey" computer aided design system industry was born.

The interest in computer graphics became international with the United Kingdom, Hungary and Japan becoming especially involved in the development of new applications. The yearly Computer Graphics Conference in London gave rise to a public forum for the presentation of papers describing the newest developments in the application of computer aided design. In 1979, an international conference on the application of computers in architecture, building design and urban planning was held in Europe. Electronic circuit design and manufacturing, however, were the bigger beneficiaries of the developmental process as a practical and profitable application of computers in the design process.

Unfortunately, the impact of computers in practical structural engineering has been somewhat disappointing. Much of computer programming in this area has benn developed within the academic field or by government funding. Hence, many programs are too limited in scope for practical use.

The General Accounting Office (GAO) study of 1980 of computer aided design usage in Federal government construction projects argues the fact that Federal agencies are not actively seeking or encouraging the use of computers on Federal design projects. Villanueva, in his 1977 paper concluded the lack of usage of computers in structural engineering work was due to excessive costs. He further identified ten basic contributing factors to the undesireable computer costs [3]:

1) Managerial ignorance or ego. Development of programs which are a duplication of proven existing ones;

2) Poor programming development by not incorporating efficient numerical computer operations;

3) Poor estimates on computer processing time required when running a particular program;

4) User ignorance on how the computer is solving the problem;

5) User manuals are either poorly written or nonexistent;

6) Extravagant mathematical modeling of the structure;

7) Lengthy preparation of numerical input for the program;

8) Needless repetition of program runs due to careless inpput or output planning;

9) Excessive unnecessary output or omission of necessary output; and

10) Failure to tie together the different disciplines in analysis, design, detailing and construction during the process.

Although characterized as disappointing [4], the use of computers in the architectural and engineering arena is considerable. A 1978 GAO study surveying 800 architectural and engineering firms, not selected on a statistical sampling basis, showed 76.1 percent of the 745 responding firms used computers in some way during the design process in providing design services to their clients. The firms reported usage of computers was mostly in the engineering areas, but indicated a trend toward using computers in the specifications and cost estimating areas. Figure 1 [5] shows a breakdown of the type of firms and respective usage of computers.

Type of Firm	Total	Users	Percent
Architect	186	73	39.2
Engineer	200	190	95.0
Architect-Engineer	318	276	86.8
Other	41	28	68.3
Total	745	567	76.1

Fig. 1: Firms Using Computers in the Design Process

The interest of architectural and engineering firms and Federal agencies, spurred by the GAO study, in computers has not gone wholly unobserved. The turnkey vendors of computer aided design systems have recently recognized the potential of this market and are already moving in that direction as

exemplified by the recent CALMA Corporation's decision to establish a new division to deal specifically with this market.

B. COMPUTER AIDED DESIGN SYSTEMS

The 1978 GAO study also reported of the 567 firms utilizing a computer in the design process, 252 firms owned their own computers. These were the larger firms. Owning one's own computer is not the only way to introduce the computer into the design process. There are several possible methods of obtaining the assistance of a computer, figure 2 provides a complete breakdown on how computer services were obtained by the various firms [6].

Method Used	Arch.	Engr.	Arch.-Engr.	Other	Total
Firm owns a computer	9	90	137	16	252
Firm leases a computer	5	16	43	4	68
Firm uses commercial time-sharing serv.	18	93	141	14	266
Firm uses commercial service bureau	16	62	85	7	170
Consultants provide computer services	30	23	61	3	117
Other	6	9	8	3	26

NOTE: Firms may use more than one type of service.

Fig. 2: How Computer Services Are Provided

The 1980 GAO study provides an insight in the continued proliferation of computers amongst the architectural and

engineering firms. The study offers eight potential ways computer use can improve designs [7]:

1) Permitting rapid study of design alternatives to provide a high quality building;

2) Providing a tool to quickly evaluate options when project costs must be reduced, or major material or equipment component substitutions must be made due to a supply shortage or change in criteria;

3) Permitting building designers to completely evaluate and incorporate energy conservation and environmental considerations during the design process;

4) Providing completed designs and drawings containing fewer errors and without the inconsistencies possible with manual methods;

5) Providing a systematic process to determine and eliminate interferences between building subsystems and components through an interactive redesign process;

6) Providing a means of reproducing construction instructions, e.g. specifications and drawings, quickly and accurately;

7) Providing cost savings or good dollar value for expenditures because the design team has the ability to consider and evaluate more alternatives and eliminate gross overdesign; and

8) Providing a quickly usable reference base for future maintenance and major modifications/renovations because of changes in building use and/or occupant.

Most systems are not yet so sophisticated to permit the achievement of all of these eight potential benefits in total. Each system does attack a subset of the above list giving the user the choice of which system is best suited to his needs and match his economical environment. Lazear, as shown in figure 3 [8], provides us with a hierarchy of system characteristics which take advantage of some possible subsets of the above benefits.

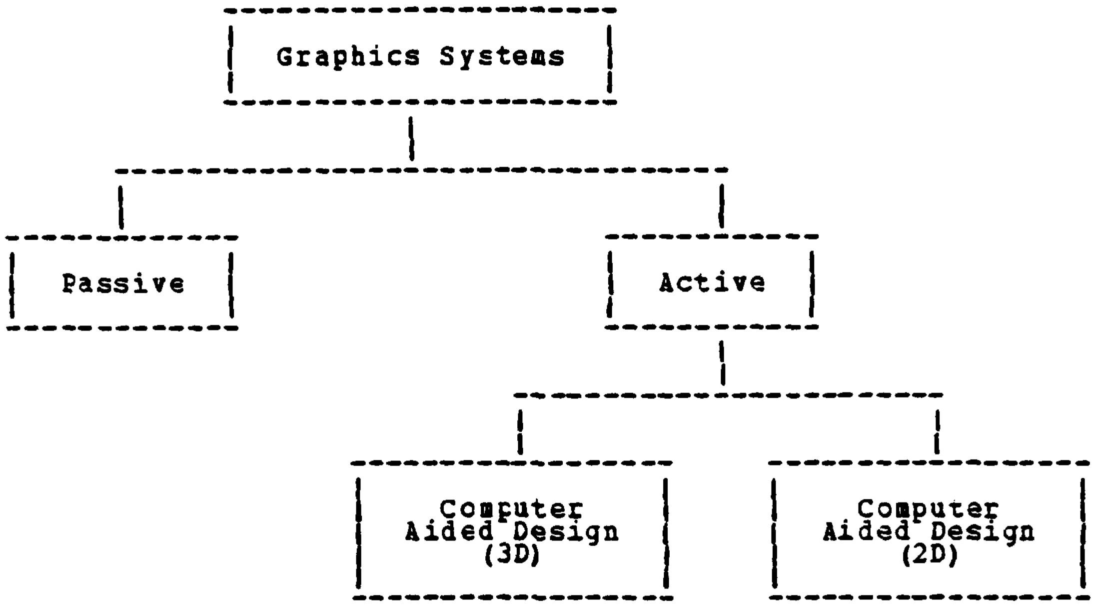

Fig. 3: System Characteristics

Most of the systems dating back to the mid 1960's and 1970's were of the passive variety. Passive simply means that the user is required to develop his design on a data media, usually in the form of cards, submit this media to a computer and wait for the finished output. It was achieved by making the software smart enough to take a description of a part and generate a drawing, automated drafting. This required a very large and complicated program or a very simple part. Several of the large engineering construction companies use a passive, automated design approach to piping isometrics, ideal for a process plant project. The disadvantage is inherent to the batch mode of operation, the drafter or designer has no immediate feedback.

The active system is the ideal for designers. Active graphics implies that the designer can directly participate with a computer in the creation of a drawing. The designer can see the product of his work on a graphics CRT and can input changes interactively through some device such as a light pen or digitizer. The active systems are further subdivided into the computer aided drafting and computer aided design.

Computer aided drafting is a cheaper and less complicated system where the computer has no knowledge of the physical object being designed. It simply keeps track of standard symbols or groups of symbols and quickly puts them on the drawing at the user's command.

Computer aided design is a more expensive alternative which requires a much "smarter" computer. The problem shifts from simply keeping track of a list of symbol types and locations to keeping track of this plus an enormous amount of information which accompanies design, e.g. different aspects of physical components, materials, sizes, colors, codes, etc.

An architectural and engineering firm has an enormous number of options in the computer aided design arena, both in approach and design. These options can essentially be

fitted into four distinct categories of hardware/software solutions [9]. Listed with each category is a sample of available applications:

1) Use a service bureau; three dimensional CAD, structural and piping isometric;

2) Tack software and terminals to your in-house maxi; three dimensional CAD, structural, piping isometric and MIS graphic;

3) Buy a turnkey package; IC design, structural, building layout, flowsheets, diagrams, tool design and piping isometrics.

4) Experiment with a hobby computer; small calculations and pictorial.

By far the most popular solution to design is the turnkey system package, generally implemented on minicomputers which are dedicated to the function. Each of the four options is commercially available through a variety of firms. The four options with a partial list of vendors are illustrated in figure 4 [10].

Computer aided design offers a solution to some of the problems faced by engineering companies today. Technological advances have improved systems so that there is a large number of application approaches to choose from, providing great opportunities for increased productivity. The selection of the system should be viewed carefully, with a review of all practical alternatives with a broad selection of management is the best approach to use to ensure system success and usage.

Graphics Systems

Service Bureau	Maxi	Turnkey Mini-Based	Home/ Hobby
McAUTO-CADD COMPAID	CDC TIGS	APPLICON	APPLE
CDC CYBERNET	IBM	AUTOTROL	PET
BOEING		CALMA	RADIO SHACK
LOCKHEED CADAM		CAL COMP	VECTOR GRAPHICS
		COMPEDA	
		COMPUTERVISION	
		EVANS-SUTHERLAND	
		GRAPHICS CONSTRUCTION	
		HOLGUIN	
		HP	
		M & S COMPUTING	
		TEKTRONIX	
		TERAK	
		T & W SYSTEMS INC.	

Fig. 4: Representative Alternatives for Hardware/Software

II. DESIGNING WITH INTERACTIVE GRAPHICS

Computer graphics has become, for some, almost syncnymous with the terminology of computer aided design ever since the classic work of Sutherland [11] in 1963. This can be attributed, in part, to the historical development of CAD as a tool first explcited in the areas of computer drafting and integrated circuit layout design, where graphics is an indispensible tool. The use of graphics as an element in the overall design process accentuated the need for improvement in the interface of this element with the rest of the design process. In particular the development of input procedures of data had to keep pace with the advancements in computational techniques if graphics was to remain a cost effective element of the design process [12].

The attractiveness of having an interactive graphic system as an element of the design process lies in its potential to exploit the powerful capabilities of human visual data-processing as a natural interface between man and the computer. The result of each input operation should be repeated on the display, so that the user can appreciate the effect of his input and take corrective action if

necessary. The more immediate and complete this feedback, the easier the user's task. The cathode-ray-tube (CRT) has become the dominant display technology [13] in console-sized displays. A survey of input devices for graphics, primitives and screens is presented as an evolutionary treatment of input procedures and graphic systems.

A. INPUT DEVICES FOR GRAPHICS

Data entry from a keyboard requires a precise definition of the x and y coordinates in absolute numerical values. It is generally more important to position one point relative to another, and therefore unnecessary to use absolute data entry as the primary input mode. While alphanumeric information and graphic and program control instructions may be generated on a keyboard, it is generally more convenient for the user to be able to select a command from a displayed list without interrupting the graphic interaction. Therefore, interactive computer graphics consoles require at least one additional graphic input device for use in conjunction with the display. A graphical input device is necessary in order to have some means of transferring geometrical and topological information to the computer.

There are a variety of methods which might achieve this. Before describing these it is well to examine the

requirements of such an input device; naturally, these depend on the application of the system. Graphic input devices perform three distinct functions [14]:

1) selection of a particular item from a display array, e.g. a graphic symbol, a numerical component value for input data to a program control instruction;

2) freehand sketching of pictorial data in the form of line drawings; and

3) digitization of original hard copy, e.g. maps by tracing.

The effectiveness of an input device should be judged against the following criteria [15]:

1) it must be simple and natural to use, requiring little or no user training;

2) the interface between input device and computer should be simple;

3) support software must be minimized so that maximum main memory storage may be dedicated to display control;

4) the device and its interface should be inexpensive, versatile and capable of interaction with different types of display; and

5) the provision of hard copy or the facility of touch interaction without a special stylus may be considered essential to the user situation.

In some applications, graphical information which is entered into the computer can be described as "non-analytic". Typical of this type of information are contours on maps and other geographical data, and experimentally determined curves. This kind of information is not suitable for transmission to a computer since it is

in analog form. The input device must convert the data in digital form linearly and accurately. Since there are no formulae for generating such curves, the computer can do no more than store the data as a series of points, each represented by one pair of coordinates. It is easy to fill a large store quickly with long strings of closely spaced points when data is of this form.

The designer tends to see things differently from the way the computer is best suited to handle them. For instance, most designers visualize triangles, quadrilaterals, cr similar figures as areas bounded by lines which meet at ccrners. The computer is best suited to working in the fashicn of coordinate geometry. storing a triangle as three points. It is the difference in the ways that machines and designers handle data that makes interactive graphics such a potentially powerful tool. It is ,therefcre, desirable, indeed critical to try to facilitate the mediation and decision processes by appropriate design of the system, especially the information input and output (response) features of the system.

A great variety of input techniques have been developed. These various techniques can be classified into four major categories [16]:

1) mechanical input devices;

2) the light pen;

3) electronic data tablets; and

4) touch-entry devices.

1. Mechanical Input Devices

These mechanical input devices consists of the joystick, the tracker-ball, and the mouse. All three devices operate on the same basic principle of generating simultaneous x and y cocrdinate data by means of a mechanical coupling to mutually perpendicular potentiometers or shaft positicr enccders. Their cperation relies on visual feedback from a dynamic display. It should be noted that these devices are not considered suited to interactive computer graphics applications. Mechanical devices are more suited to a tracking type application such as radar tracking where they are cften used to control the rate of movement of the cursor rather than its position. The actions of an interactive graphics user are more directly connected with drawing than tracking. Although one can draw utilizing mechanical input devices, the operation is an awkward one.

2. The Light Pen

A truly interactive instrument, the light pen is composed of a light-sensitive device which detects the existance of a pulse cf light within its field of view, e.g.

the emission from the phosphor of a CRT display. The optical coupling may be direct to a photodiode housed in the hand-held "pen" assembly, or via a fibre-optic light guide to a photomultiplier tube. In either case an "umbilical cord" connects the pen electrically or optically to the console equipment. Input may be inhibited either by a mechanical shutter, by an electrical switch in the pen or by a footswitch.

The operation of the light pen depends on the nature of the process of writing an image on the face of a CRT. If the pen is pointed at the screen and the spot which is generating the image passes through the visual field of the pen, then the light-sensitive device is energized and a signal passes to the computer, generally causing an interrupt, that is, a jump from the current program into a special routine. Upon detection of this interrupt, the computer goes into a search routine to determine which command the display processor was obeying when the interrupt occurred. From this it can determine the coordinates of the point on the screen at which the light pen is pointed. This gives the light pen a significant advantage over other input devices. Specifically, that its positional data is determined by the program and does not depend on any

physical measurement of the actual pen position. The cursor is on the screen itself and can easily be aligned to any target image, to the limit of human accuracy.

The light pen has two modes of operation, the pick function and the cursor mode. The pick function selects the character or figure of interest. The cursor mode allows the "pen" to be used to position a reference tracking-cross on the desired location. In this way, isolated points, end points of vectors and centers of circles, for example, may be delineated.

3. Electronic Data Tablets

There exists many forms of electronic data tablets, including several types of acoustic tablets. A data tablet is essentially a rectangular panel which represents the area of the display. The tablet surface, which is generally electrically conductive, may be driven at its edges to produce over its area a linear gradation of an electrical signal such as voltage amplitude or phase. Opposite pairs of edges are generally switched alternately to produce accurate, linear parameter gradients in both the x and y directions. More sophisticated tablets would be able to remain electrically active for both x and y directions simultaneously. The signal at a particular point is

detected by a high impedance sensor within a *movable,* hand-held stylus whose position is thereby uniquely encoded. An alternate design may allow the stylus to disturb a field pattern on the tablet surface. This disturbance is detected at the edges of the tablet and measured in terms of stylus position. There are many commercially avilable data tablet types, notably those which comprise two or more flexible, conductive layers which make contact with each other at a point where stylus pressure is applied to the upper surface.

4. <u>Touch-Entry of Graphic Data</u>

Touch-entry devices allow the user to work directly on the display surface without an interface, e.g. the light pen "umbilical cord". The touch-entry devices provide maximum convenience by positioning the input device as a touch-sensitive overlay to enable the generation of coordinate information directly at the display surface by the user's finger without the user having to pick up a special stylus. This allows for maximum visual feedback between the display and the user. The cursor is positioned in the chosen location by the user referring to the cursor and not to the exact finger position, although cursor control is achieved by finger movement. There are two categories of touch-sensitive devices, namely those which

permit the addressing of a limited number of discrete, predetermined points or areas and others which provide a continous coverage of the display screen.

5. <u>Handling Graphical Input Devices</u>

The two basic tasks of an input device are to indicate objects on the display, and to input two-coordinate data not necessarily corresponding to anything being displayed.

The light pen, for example, performs the first task when positioned over the indicated object, generating an interrupt whenever the display processor deals with the object. However, it can be used only to signal points which lie on displayed objects. In order to indicate an arbitrary point, the program must be persuaded to display something there. A common approach is the use of a tracking symbol such as a cross. When the light pen is placed at the periphery of the symbol, the program repositions the symbol so that its center lies under the light pen. The tracking symbol will follow movements of the light pen.

Other devices, such as electronic data tablets and mechanical input devices, can generate a two-coordinate data input independently from the display. Again, a display symbol is utilized. It is centered on the point currently

generated by the tablet so that the user has visual feedback of the input. However, the tablet or mechanical device cannot by itself identify the display-file instruction currently generating the object at the cursor position. A comparator [17] can be used if available. This accepts coordinates such as the display symbol position, and generates an interrupt when a point is displayed at those coordinates. In the absence of a comparator, the display-file must be searched for points at the display symbol position.

A device such as an electronic tablet gives a continuos positional input, and means must exist to indicate whether the input is significant, e.g. a button which generates an interrupt for the processor causing it to read the position. Light pen tracking, however, is usually done by an indipendent service routine and does not generate interrupts. Attention must be drawn to the light pen by some ther device such as a keyboard.

B. PRIMITIVES

Current literature suggests, if not a direct consensus, that effective integrated CAD systems incorporating interactive graphics requires the development of fully three dimensional isotropic representation of the model. The

initial model, directly input by the designer, is processed "downstream" for all the functions of the engineering organization [18]. The essential nature of graphics involves the additional capability to describe geometrical properties. These geometrical properties are essentially points and lines connecting the points. Systems vary greatly in the manner in which these primitives, particularly lines, are defined. The particular method of implementation is best dictated by the requirement of the application [19].

The CAD system which is to support an architect and engineer design effort should have available interactive devices which provide the user with a fast and simple mean of imputting three dimensional data. This three dimensional data should be able to represent objects with sufficient complexity so as to be meaningful in an architectural design environment, and it should be usable by other available software packages [20]. The primitives employed to describe the geometrical properties of the three dimensional object need to be able to support four types of transformations required as basic capabilities for graphics applications [21]:

1) Shifting. The performing of an additive transformation of the x, y and z coordinates of all points of an object by some delta amount, e.g. $x' = x + k$. The result is a size-variant spatial translation of the object;

2) Scaling. The performing of a multiplicative transformation of the coordinates of an object by obtaining a product of some scaling factor, e.g. $x' = xS$. Unequal scaling may be applied to each axis, in which case the object is compressed or attenuated. The result is compression for $S < 1$, magnification for $S > 1$, or reflection about an axis for negative values of S;

3) Rotation. The performing of a trigonometric transformation of an object coordinates, e.g. $x' = x\cos A + y\sin A$ where A is the angle of rotation. The result is a rotation of the object about an intrinsic axis by angle A;

4) Clipping. The defining of a rectangular area of the total viewing space such that only the object points which are within this space will be viewable; and

5) Windowing. Not a true transformation, but commonly utilized. It is derived by first involving a clipping transformation of the view with the additional provision for other transformations simultaneously to be made.

Geometric representation of primitive volumes can be accomplished through a build up procedure from points and lines or a "library" of basic volumes, e.g. a databank of predefined primitives such as cylinders, cones, and cuboids. The use of points and lines as a build up procedure is a time consuming task which would quickly exasperate the user. A library of basic volumes has to be the preferred method, and is the one utilized by commercially available systems. The problem with any input system is the identification of intersections and boundaries, and hidden points, lines, and planes.

1. Geometric Modelling

Let us suppose the problem is to determine whether a certain point is inside or outside the image. The designer can decide after a cursory visual inspection. For the computer to draw the same conclusion it needs to perform a series of tests and calculations. If the images are to be realistic, the computer must be given instructions for solving the hidden points, lines, and planes problem. The mathematics for such a program are fairly complicated. Let us assume a hidden plane problem exists for an image. For such a problem the program must enable the computer to answer four categorical questions [22].

The first question is whether or not the plane is visible by itself. In answering the question the computer must calculate the perpendicular to the surface of the plane. If the angle between the perpendicular and the direction of view is acute, the plane is visible. If the angle is obtuse, the plane is not visible.

The second question is whether or not the plane is obscured by any other plane within the same cluster of planes. Here the computational process is rather long, but it need be done only once. The resulting ordered list of planes is stored in the computer's memory.

The third question is whether or not the cluster of planes is obscured by any other cluster of planes, e.g. two cubes sharing a common face. Here the order in which the clusters are displayed depends on the orientation of the two cubes, in other words on the view the designer has choosen to display.

The fourth question is whether or not the object is obscured by another object, e.g. the two cubes being displayed with two other cubes on the same image, but constituting two separate objects. In this case range points are assigned to the two objects, and the order in which the objects are displayed is then determined by their distances, that is their relative ranges or positions assigned by the designer.

These calculations and tests would be difficult, if not impossible, if the computer had to deal solely with graphical image inputs. The inadequacy of a graphical image arise for three reasons [23]:

1) the descriptions which they generate are geometrically incomplete;

2) the descriptions generated are highly redundant; and

3) the geometric information is inadequately structured.

A complete geometric description of an arbitrary point allows unambiguous determination of whether that point

is on any specified line or space, or within any specified closed region. Images are invariably geometrically incomplete because they represent a three dimensional object as a series of two dimensional projections. It is the nature of two dimensional projections as standardly used in architecture that points may appear in different projections. For example, the x and y coordinates of a point may be defined in one drawing and the y and z coordinates in another. Thus, the y coordinate is represented redundantly.

An image stored as a set of projected coordinates and lines is not an appropriate structure for the performance of many operations that are important in architectural and engineering computer aided design. Data to be operated upon, that is analyzed, must be structured in appropriate ways if algorithms are to be expressed concisely and clearly and executed efficiently.

By contrast, a true three dimensional geometric description system stores representations that are geometrically complete, relatively nonredundant, and appropriately structured. The graphics interface allows images to be generated with any specific scale and projection, from any specific direction, sectioned in any

specified way. Thus, a three dimensional geometrically described object is much more general and powerful than a graphically described image.

2. <u>Geometry</u>

A complete geometric description includes relations between entities and shape and dimensional data. There are three basic ways of encoding geometric data [24]:

1) point set technique;

2) boolean technique; and

3) boundary technique.

a. Point Set Technique

The point set technique is the most straight forward. It derives directly from the classical definition of a solid body as a set of contiguous points in Euclidean space. To any specified level of resolution, a region of Euclidean space can be represented by a three dimensional array in which each location corresponds to a point. A solid object within this space can be described by assigning the value "TRUE" to each point within the object and the value "FALSE" to each point not within the object, as shown in figure 5. A three value logic can be used, with the third value employed to represent points on the object's surface [25]. An assembly of many solid objects can be

encoded by using a different integer to represent each different solid. This technique has been widely employed to represent building floor plans [26].

FALSE	FALSE	FALSE	FALSE	FALSE
FALSE	TRUE	TRUE	FALSE	FALSE
FALSE	TRUE	TRUE	TRUE	FALSE
FALSE	TRUE	TRUE	TRUE	FALSE
FALSE	FALSE	FALSE	FALSE	FALSE

Fig. 5: Point Set Representation of a Shape

The point set approach has the advantage of providing spatial indexing. However, it requires a large storage capacity by the computer where high resolution description of a complex object is required, and its point by point mode of description makes it undesireable for many applications. These disadvantages make the point set approach impractical for most three dimensional shape description purposes in support of architectural and engineering computer aided design.

b. **Boolean Technique**

The Boolean approach uses the idea of directed surfaces. A directed surface divides the universe into two disjointed point sets. Points in one set, on one side of the surface, are labeled "TRUE" and points in the other set are labeled "FALSE". A number of different directed surfaces can be defined, and solid objects can be described by performing operations of union, intersection, and difference on point sets, as shown in figure 6 for a two dimensional object. Solid objects thus created can be further combined in various ways using the same Boolean operations.

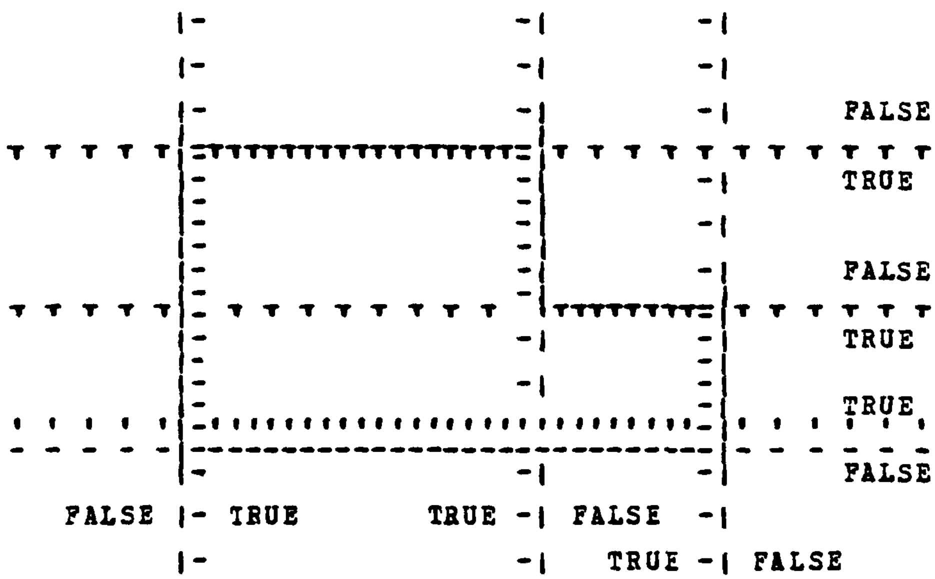

Fig. 6: Boolean Description of a Shape

The Boolean approach is much more economical in use of storage than the point set approach, since it does not require explicit storage of the values of points. One needs only to define the equations for the surfaces, the senses of their normals, and the Boolean operations. However, Braid has identified a key disadvantage in the computational requirements which the Boolean approach imposes on the computer in order to display any solid object [27]. Any object composed of n faces which is held as the intersection of n directed planes to draw all edges requires computation of the order n cubed. This is due to the necessity of the computer to compare each of the n planes with each of the n-1 other planes. The line of intersection found, assuming no planes are parallel, needs be compared with the n-2 remaining planes to find the portion of the line, if any, lying within the n-2 planes.

c. Boundary Technique

A boundary model describes a solid object by recording the coordinates of its vertices and the coefficients or equations defining the forms of boundary lines and surfaces, as seen in figure 7. Straight lines and planar surfaces are easily represented by simple equations. There has been an enormous amount of research on curved

surfaces, developing the mathematical theory sufficiently to deal with any practical architectural description problem. The work of Bezier, Coons, Forrest, Riesenfeld, and Levin is particularly important.

```
      (x',y') o-------------------o (x",y")
              |                   |
              |                   |
              |                   |
              |          (x"',y"') o---------o (x"",y"")
              |                              |
              |                              |
              |                              |
 (x""',y""')  o------------------------------o (x""",y""")
```

Fig. 7: Boundary Description of a Shape

A great advantage of the boundary model is that it allows topological and geometric information to be stored separately. Connections between faces, edges, and vertices, which form one component of the model, are stored in some form of incidence or adjacency matrix. Real numbers defining vertex coordinates and coefficients in equations are stored elsewhere. This is very convenient, since some shape manipulation operations alter just the topology, some alter coordinates and coefficients, and some alter both. In addition, it provides an opportunity to factor the data, since numerous geometrically differing objects may be

instances of the same topological structure, e.g. a cube, a rectangle, or any other cuboid.

Since vertices, edges, and faces of a solid are defined in terms of each other, conversions from one to the other can be made easily. Thus, it would be redundant to describe all three types of entities explicitly. Boundary models have been utilized in several shape description systems, such as the BDS system for architectural building description [28].

C. DISPLAYS

The geometric description, once obtained and stored in the computer, serves two essential purposes:

1) as a databank to be acted upon by the various application programs; and

2) as a source of information to allow the object to be displayed.

Designing with interactive graphics presupposes the use of a display element upon which the designer can view the object and which can act as an input-output medium. These display elements have their own requirements placing additional demands on the computer system. The cathode-ray tube (CRT), in one form or another, is the universal graphic display device. The nature and principles of operation of CRT's are well described in texts on electronics. There are

some features of CRT's, however, which impose important constraints on the design of computer graphics systems.

CRT's as display elements are designed to utilize data in the analog format. Since data within the computer is in the digital form, a digital to analog conversion must occur for the data to be displayed. Conversely, an analog to digital conversion is also necessary to transmit to the computer positional information as inputted from the various input devices mentioned previously. In addition, depending on the display element utilized, an image must not only be generated once, but must be regenerated on a periodic basis to maintain the image on the display visible to the user.

In order to display an object on a CRT three voltages must be supplied per each position or spot. An horizontal and vertical deflection voltage is required to locate the spot on the display, and a modulating voltage is utilized in the control of the brightness of the spot. The computer must supply the instructions necessary for displaying the spot on the CRT. The sequence of instructions is as follows [29]:

1) generate the horizontal and vertical coordinates;
2) convert them to voltages;
3) generate and convert the brigthness voltage; and

4) repeat the process with a predetermined frequency to maintain the spct on the display.

Constant image maintenance can be avoided by utilizing specially designed storage tubes such as the direct view storage tube. The principle of operation of the storage tube depends on the phenomena of secondary emission due to electron bombardement. Certain materials have a secondary emission when bombarded by electrons. A fine mesh of this material is positioned behind the screen which, when bombarded, will generate secondary electron emission maintaining the image. There are several disadvantages with such a system when utilized as a graphic display. It cannot have a resolution better than the mesh of the grid and it has a low light output which entails operating such a system in an environment of subdued lighting. The principal disadvantages, however, are that it cannot be selectively erased, that is, parts of the image cannot be individually deleted; and that a light pen device will not work since continuous refresh, upon which the light pen depends for the emission of the phosphor, is not used [30].

In addition to the CRT, a raster type display is also widely used for graphics. The raster type display draws and regenerates the image by causing the electron beam to scan the display area on the tube face in a pattern of evenly

spaced horizontal straight lines. During the time of one complete raster scan, or frame, the beam passes once through every point in the display. In order to produce an image, bright-up is caused at the appropriate instants within the scan time. The display data must, therefore, be programmed in serial form, with time as a coordinate rather than the horizontal and vertical position. This is the method by which television pictures are generated and refreshed. The advantage of the raster is that it can be easily designed, due to the intensive research of the television technology, to be able to arrive at any desired resolution. Thus, a computer graphics system which requires optimal resolution of its images can be achieved with today's technology and at a reasonable cost.

III. COMPUTER AIDED DESIGN

The term "computer aided design" has taken on many meanings since computers began to have an impact on the architect and engineering field. It has been applied to any engineering design during the course of which a computer was utilized, such as the evaluation of analysis equations to predict design performance. The term has also been applied to the use of applications programs or problem-oriented languages, each of which focuses on a narrow problem and treats it in a stylized way suitable to its particular characteristics. Often, this has the nature of answering the same design questions about problems cast into a standard form demanded by the program. They provide analysis, while the designer wants synthesis.

Computer aided design should aim at organizing the analysis and search activities of a designer as he attempts to find values for the independent design parameters at his disposal so that specific performance goals will be met [31]. To achieve this the "computerized" design process has undergone through several stages of development, automating several design areas through the successful use of discrete application programs. It became quickly apparent , however,

that the limiting factor for success included the cost of data preparation and integrity.

To better understand the evolution of computer aided design systems for the architectural and engineering field, a discussion on design theory, the data base problem, and design analysis is presented.

A. DESIGN THEORY

The availability of computers rekindled the engineer's interest in the general models of physical systems since such models could more easily be adapted as the vehicle by which a computer could be utilized to solve real problems. Gabriel Kron's network models are a typical example. Kron was largely concerned with analysis. He developed some very general network models and some highly effective schemes for dealing with these models numerically in attempting to predict behavior in a wide variety of physical situations. Having many areas of analysis well in hand, interest has been turning to questions of design and whether Kron's work could be carried over into this area usefully.

Superficially, at least, all of design shares concern over questions of the assembly of elements to form an entity, decomposition as a means of dealing with combinational problems of size, artificial intelligence and

heuristics, optimization, etc. A review of "BASIC QUESTIONS OF DESIGN THEORY" (Spillers ed.) would give the reader an insight into the diverse views and technologies relevant to architectural and engineering design theory. The design theory is presented in vertically structured design activities along the classical lines of the various design disciplines. Subsequently, Spillers presents the possibility of viewing these activities horizontally, which is, perhaps, more beneficial when considering the computer as an aid to design and the set of new problems such an aid represents. Such a view would provide us with the following areas of interest [32]:

1) Graph Theory;
2) Heuristics;
3) "Wicked" Problems;
4) Linguistic Methods;
5) Behavior;
6) Aesthetics; and
7) Composition Techniques.

Behavior and aesthetics takes us into the realm of behavioral science and artistic creativity in design, while composition techniques is more frequently encountered in the chemical engineering discipline. The first four areas of

interest listed above impact more directly on the computer aided design system as it has evolved to date.

1. <u>Graph Theory</u>

The mathematician Harary [33] presents a convincing argument on the prevalence of graph theory as the strongest thread of formalism running through design. Much of design is concerned with the assembly of elements to form as entity. In many cases, the elements from which a selection is to be made are fixed and in most cases, they are discrete elements. The question of the connectivity of a discrete system is, of course, a graph problem. The use of graph theory has become so common throughout all of engineering design that it can now be taken for granted.

In engineering analysis, the work in graph theory led to the formulation of generalized network theories which include wide classes of physical systems and to the extraction of some useful results for these systems based upon their graph theoretical properties. The question then arises concerning the useful role of graph theory in computer aided design. The problem appears to lie in the fact that graph theory is not sufficiently rich in structure to support an activity as complex as computer aided design.

The composition problem for graphs is a case in point. While on an elementary level, graph theory and network theory are almost inseparable, the problem of the addition of two graphs or the building of a new graph from two given graphs can have many interpretations [34], all of which lack physical relevance and thus tend not to be of direct use. In the computer aided design arena, graph theory can no longer be looked to as the formalism of design theory. While a graph can be used to represent a binary relationship, more complex relationships for bringing out underlying structure must depend on other representations such as the three dimentional geometric representation previously discussed.

2. Heuristics

The practice of design today is the realm of heuristics. In general terms, Himmelblau [35] suggests that design is essentially a search process in which the more organized design studies represent perturbations about existing designs. Creative solutions represent radical changes in search procedures for which there now exists no adequate theory. Artificial intelligence was to provide the tools, but that has not been the case. Nevill and Crowe [36] reported this failure in the progress of artificial

intelligence as generating a trend in the computer aided design system development towards a strong man-machine interface which allows the computer to be helpful, but which relies heavily on the designer for logic in the design process, the designer is the synthesizer.

Heuristic search is probably the remaining stronghold of artificial intelligence. The area of heuristic search remains an important aspect of the design process since combinatorial problems obviate methods of exhaustive search. Problems of overwhelming size require decomposition techniques to reduce them to workable pieces. With some exceptions for which the algorithms of the problems are known, decomposition is also the realm of heuristics. The work of Kron relates directly to the developing methodologies of decomposition as used in design.

3. "*Wicked*" *Problems*

Both the breadth of an activity and the diversity of opinion are enormous in design theory. J. Christopher Jones [37] presents us with some definitions and descriptions of the design process:

> Finding the right physical components of a physical structure (Alexander, Christopher).
>
> A goal-directed problem-solving activity (Archer, L. Bruce).
>
> Decision making, in the face of uncertainty, with high penalties for error (Asimow, M.).

Simulating what we want to make (or do) before we make (or do) it as many times as may be necessary to feel confident in the final result (Bocker, P. J.).

The conditioning factor for those parts of the product which come into contact with people (Farr, Michael).

Engineering design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform prespecified functions with the maximum economy and efficiency (Fielden, G. B. R.).

Relating product with situation to give satisfaction (Gregory, S.).

The performing of a very complicated act of faith (Jones, J. C.).

The optimum solution to the sum of the true needs of a particular set of circumstances (Matchett, E.).

The imaginative jump from present facts to future possibilities (Page, J. K.).

A creative activity - it involves bringing into being something new and useful that has not existed previously (Reswick, J. B.).

The first surprise about these quotations is that they differ so much, only about a tenth of the important words are mentioned more than once. There seems to be as many kinds of design process as there are writers about it.

The very fact that there is a discussion of design theory is encouraging. This would almost imply that the participants believe that a high degree of automation is possible in design. Evidence of the past ten years shows us in fact there is an increase in automation, but what many designers are concerned about is the role of automation in design. "Wicked" problems are an interesting case in point,

and represent the strongest bastion of resistance to automated design.

The degree of automation of an activity seems to run inversely with its complexity. As a result, architectural design which is one of the most complex design activities has been the least automated. Keying upon the lack of success with automated architecture, Salvadori [38] has drawn the analogy between automated language translation and automated architecture claiming that their whimsical natures obviate automation. Bazjanac [39] has carried the argument one step further claiming that architectural design is a "wicked" problem which:

1) has no definitive formulation (since a formulation implies a solution);
2) has no stopping rule;
3) has no solution in the absolute sense; and
4) each of which is unique.

Automated design now seems to be in the middle ground in which crude methods are inadequate while complete detail is impossible. We remain in the realm of computer "aided" design, where the computer is applied to "aid" the designer and the design process rather than to generate a design.

4. Linguistic Methods

The inadequacies of graph theoretical models in dealing with sophisticated applications are reflected in the recent work on linguistic methods [40]. Semiotics, the science of the different systems of signs, might offer an important contribution to a general theory of design through the analysis of an unexplored problem: the problem of meaning. Gandelsonas [41] states that the appleal of the linguistic methods is at least twofold:

1) in such areas as architecture and picture processing there is a real concern over the "meaning" of a picture and hence an inclination toward the intuitive appeal of linguistic methods; and

2) linguistic methods represent an attempt to apply the methods of mathematical systems to problems of graph theory making available the considerable power of these tools.

He further states that linguistic methods have the potential for providing a formalism for questions of semiotics in architecture and for bridging the gap between existing design methods and the more subtle questions of aesthetics systems.

B. THE DATA BASE PROBLEM

The implementation of design theory through the traditional design process arrives at a final design description by the cumulative storing of information, as the process unfolds, in the form of drawings, such as plans,

elevations, and sections; and descriptive papers, such as schedules, bills of material, etc. This traditional approach, shown in figure 8, has the following disadvantages [42]:

1) Nonintegration. Different documents store different types of information: shapes of objects and their locations in a horizontal plane are recorded in elevation or section, cost data are recorded in schedules, and so on. Thus, it is often necessary to correlate data from several sources in order to execute a design task.

2) Redundancy. The same information often appears in several different forms in several different places. For example, a room might be drawn in several different plans, produced at different scales for different purposes. This introduces the possibility of inconsistency between different representations and makes alterations a laborious process.

3) Fixed views. Drawings give a limited set of fixed views of a building. It is more desirable to have facilities which produce sections along any arbitrary plane, perspectives from any arbitrary viewpoint, etc., as required.

4) Coordination problem. On any reasonable large project, design is carried out by a team rather than an individual. The members of the team usually work on their own copies of the master drawings and are often unaware of the actions of other members, resulting in a lack of coordination and consistency.

5) Obsolete data. Coordination problems are traditionally resolved by periodically collating data onto a new set of master drawings, which then serve as the basic reference for further work. As this is a slow and expensive process, it is not undertaken very frequently, and the data on the master drawings are therefore often obsolete.

6) Inefficient data processing. A large amount of design staff time is spent performing data processing rather than decision making tasks, e.g. copying, changing scale or format of drawings, taking off quantities, annotating, tabulating, updating, checking for accuracies, and other such tasks. Manual performance of these tasks is slow, expensive, and a major source of errors. Furthermore, it reduces the amount of time available for actual design and evaluation work.

7) Non-machine-readability. Data stored in this "paper" form cannot be operated upon directly by computer. An expensive, time-consuming, and error-prone data preparation and input step is required.

```
 ---------------          ------------
|   "PAPER"     |- - - - ->| DESIGNER  |
|  DESCRIPTION  |<- - - - -|    2      |
|               |          |           |
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    /|    |
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 |  DESIGNER  |
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```

Fig. 8: Data flow in a traditional design process

Design theory in computer aided design systems is now implemented through software, there is no "architectural" or "engineering" machine. Computer aided design software must not only be aware of the geometric representation of an image, but must also concern itself with the different aspects of physical components in an engineering design. Using piping isometrics as an example; an isometric has lines, valve symbols, notes and dimentions. In reality the pipeline being so represented, has carbon steel or alloy pipe. It has gaskets, pipe supports, different thickness bolts, may be insulated and carry all the information with respect to the type and size of insulation. It may have many other similar notations.

The data base grows enormously with this extra information. So the problem shifts from graphics and application programs to data management. We have to have not only a computer that can display shapes quickly while the designer moves his light pen, but also a machine that must be looking through massive catalogs of parts, material lists and specifications. The computer aided design system must be able to manage the data base while simultaneously managing a graphics problem and engineering change control, and doing all of this quickly enough to satisfy the requirements of an active system [43].

There is a very real detrimental aspect of incorporating a large number of independent application programs into a computer aided design system, as shown in figure 9. Such programs normally require non-standard data formats and versions which introduce data redundancy and obsolescence. In addition, their expected benefits in reducing the overall project costs may not be realized due to the cost of data preparation and input.

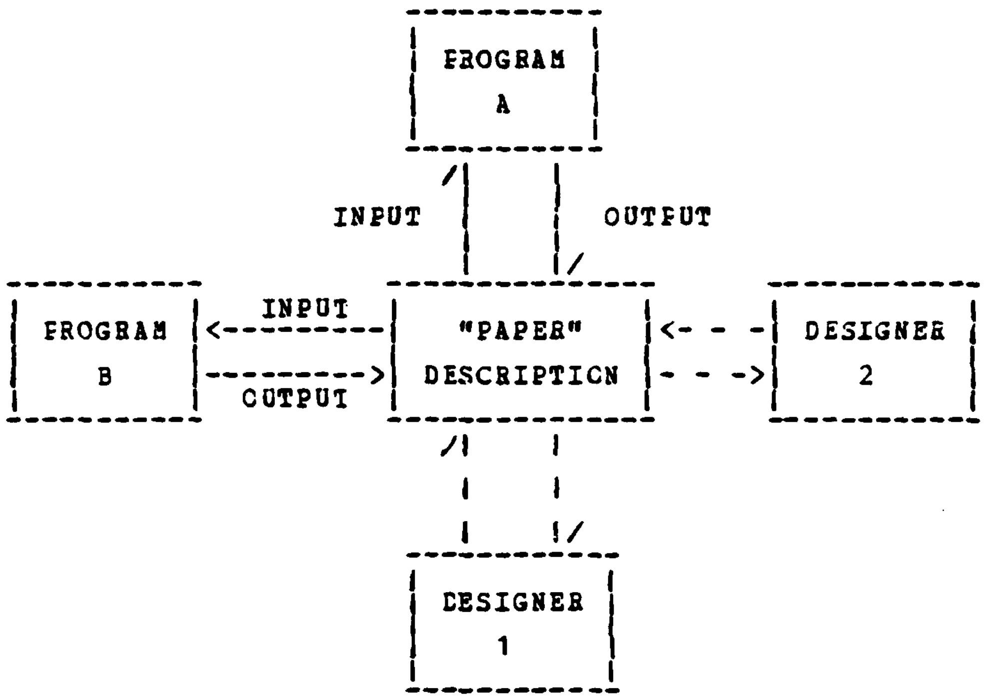

Fig. 9: Use of Discrete Application Programs

The designing of several of these programs to operate upon the same input data set would be an obvious solution, as shown in figure 10.

However, it may not be economically feasible, nor would it serve the requirements of a large computer aided design system. Additionally, this type of approach would only work well where the type of analyses are in some way similar in order to enable the programs to make efficient use of the same data structure. In other words, a demonstrated mathematical relationship must exists such that unrelated

problems can be shown to be in actuality special cases of some more generic problem where a common algorithm can be developed to deal with the full range of specific problems, thus making possible a single data structure.

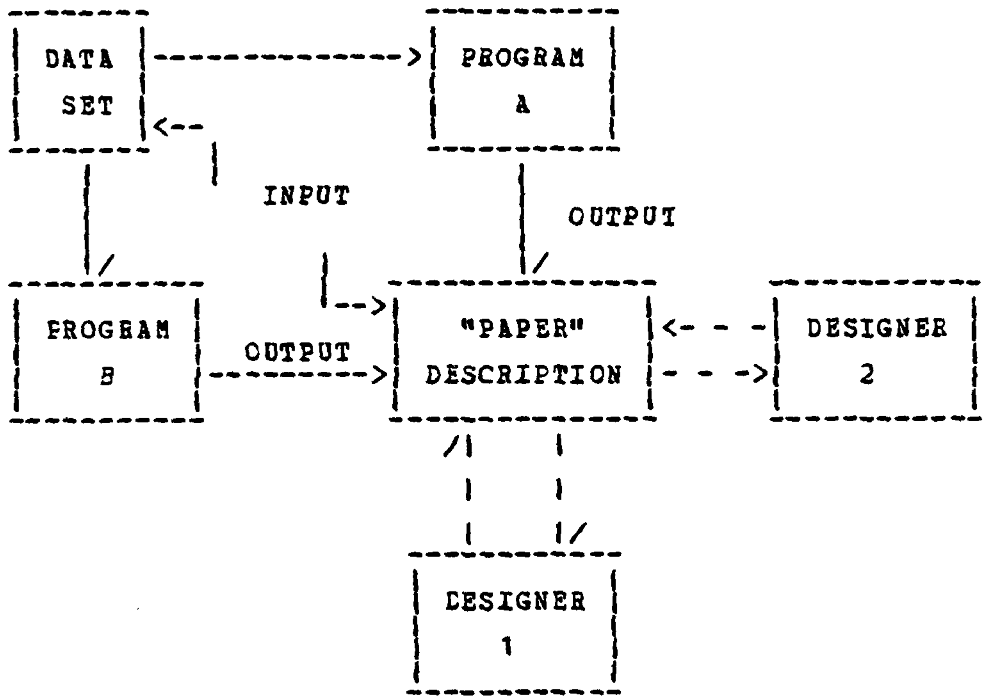

Fig. 10: Use of a Single Data Set for Several Applications

The success of linear programming methods in operation research and of finite element methods in structural engineering attest to the common algorithm possibility. In the architectural and engineering arena where such diverse applications as beam sizing, pedestrian circulation

analysis, detail thermal analysis, accoustic analysis, and other specific analyses are required, the development of common algorithms is, however, an unlikely situation.

A second approach would be to connect related programs in sequence. This approach would require the output of the related programs to be expressly formatted for use as input to the next program, as shown in figure 11. However, this approach can only be utilized where there is a very clearly defined linear sequencing in the design process, such as the thermal analysis, mechanical equipment sizing, and cost analysis. In general this is not the case. Such sequencing would also impose a too rigid linear sequence in the design process which is undesireable since a typical design task force of architects and engineers tend to progress along parallel lines in the design development, rather then sequential lines.

```
                          -----------
                         | PROGRAM   |
         ----------------|    A      |
        |                |           |
        |                 -----------
        |                  /|     |
        |           INPUT   |     |  OUTPUT
        |                   |     |
        |/                  |     |/
 -----------          -------------       -----------
| PROGRAM   |        |   "PAPER"   |<- - -| DESIGNER  |
|    B      | OUTPUT | DESCRIPTION |- - ->|    2      |
|           |------->|             |      |           |
 -----------          -------------       -----------
                         /|     |
                          |     |
                          |     |/
                        -----------
                       | DESIGNER  |
                       |    1      |
                       |           |
                        -----------
```

Fig. 11: Connection of Programs in Sequence

The best approach, with current technology, would be to organize the computer aided design system around a comprehensive data base. This can be achieved by the use of an appropriate data base management system which acts as an interface between the designer and the data base, and between the application program and the data base, as shown in figure 12. This latter interface would in fact prepare the data from the data base in the required application program input data structure.

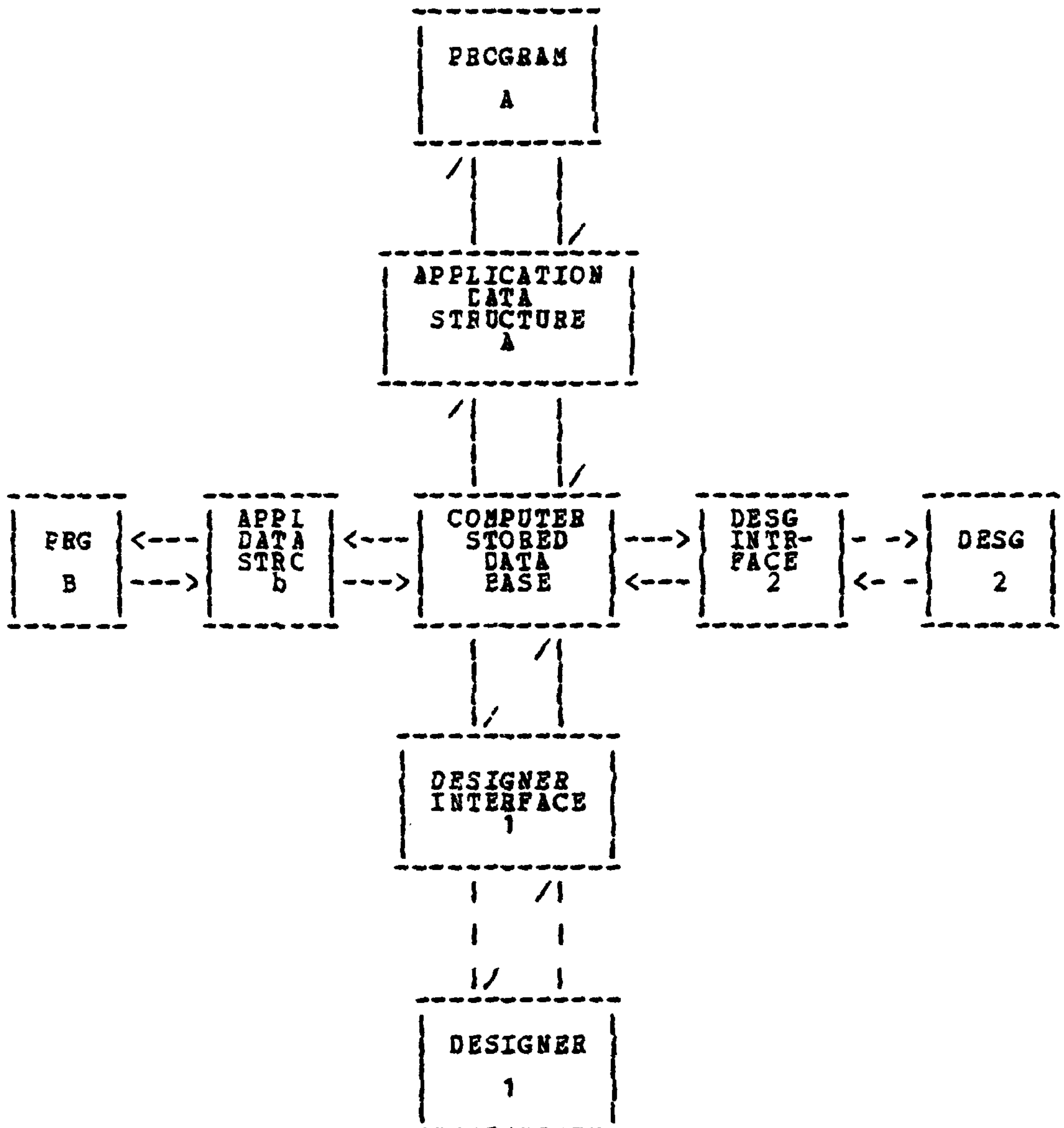

Fig. 12: Use of a Comprehensive Computer-Stored Data Base for Design Description

This approach would replace conventional paper building descriptions as the primary and definitive description of a design. Data need only be entered once into this data base

and may subsequently be operated upon by all design application programs. Drawings, printed reports, and machine-readable data sets formatted in specified ways may be generated as required through use of report-generated facilities.

From the designer's point of view, an interactive graphics work station consisting of a graphics display screen, keyboard, and digitizer tablet replaces the drawing board. The displays graphically represent the physical environment of the structure and provide a means of visually analyzing its static or dynamic behavior. The necessity for manual data handling is minimized, while the opportunity for application of computer processing is maximized.

The comprehensive data base approach provides an opportunity to effectively overcome the problem of nonintegration, redundancy, fixed views, coordination problems amongst disciplines, obsolete data, inefficient data processing, and non-machine-readability of data. Additional advantages of a data base management system are that it normally leads to more effective project cost and quality control, and simplification of project management, review, and evaluation.

C. DESIGN ANALYSIS

The use of computers in the design process enables the designers to use more accurate analysis approaches, consider more alternatives, allows for improved coordination amongst various engineering disciplines, and generally improve both the gathering of design data and its use. A computerized design process is dependent on both the hardware available to the designer and the software, more specifically the library of programs that permits the architect or engineer to "computerize" the design process. Such a CAD library of programs typically falls into two categories, the generalized programs and the specific programs.

The generalized programs are automated conditional responses to familiar situations that may be applicable to any engineering task, and are, in essence, mathematical rather than engineering oriented, such as the finite element methods. Specific programs relate directly to the kind of work being done and include repetitive problems that a particular engineering department encounters. The design of waterfront facilities provide very different engineering problems from the design of a housing complex. Specific programs should, however, be usable on different but similar projects. The economic goal of a good computer aided design

system is to have the greatest number of generalized individual programs and a minimum number of specific programs that apply to a single problem.

The analysis task can be considered of being composed of two parts, neither of which can exist by themselves. The two parts are the structure, as defined by the drawings, sketches, etc. and the analysis [44]. Defining a structure is not sufficient problem definition, an architectural and engineering design cannot be considered complete until the structure has been analyzed. The analysis must be oriented toward the answering of questions. These questions may be very specific, such as "What is the displacement of nodal point 38 under this set of loads?", or the question may be very general, such as "Does this structure under this set of loads meet the requirements of a certain section of the ASME Code?" The software should be set up to facilitate this question-answer nature of the analysis task.

As the designer develops his structure he should be able to change the performance specifications and issue commands directing searches for solutions that satisfy, or come closest to satisfying, the requirements. If the requirements conflict and admit of no solution, he can relax them in an organized fashion. If they are slack and admit

many overdesigned solutions, he can search for ways to tighten them or to balance the achievement of them. An approach is to organize the analysis and search activities of the designer and to integrate them with man-computer interaction to support the decision making processes which seem to be common to a wide variety of design problems regardless of the engineering discipline involved.

The finite element methods is a case in point. Many finite element algorithms have been developed and implemented for use by the designer for his analysis functions in several disciplines, such as structural and mechanical engineering. Elliott reports that the finite element idealization of a diesel engine piston prepared manually, occupied a qualified engineer full time for four weeks. Interactive graphic processing and automatic generation cut this time to a few days [45].

Design analysis is essentially attempting to accurately predict system performance based on the internal relationship amongst its components, e.g. the cause-and-effect relationship within the system. To accomplish this, one must construct a model that will best represent the system. One of the main strengths of mathematical models is that they abstract the essence of a

system and reveal its underlying structure. Therefore, if it is possible to obtain a reasonable idealization of the problem that is amenable for solution, such an analytical approach is usually desirable. However, due to the size and the random nature of the system components, it is often impossible to approach a problem analytically. Simulation is the practical solution [46].

Simulation also involves construction of a model that is largely mathematical in nature. Rather than directly describing the overall behavior of the sytem, a simulation model describes its operation in terms of individual events of the various components of the system. In particular, the system is divided into elements whose behavior can be modeled analytically. The interrelationships between elements are also built into the model. Thus, simulation provides a means of dividing the model-building job into smaller component parts and then combining these parts in their natural order. The computer, of course, is ideally suited for this function.

Frey, Hall and Porsching used isoparametric brick elements as the component parts in developing an interactive computer program (PLANIT) as an application of computer graphics in detecting anomalies in a finite element

idealization of a three dimentional structure [47]. Modeling for structural analysis using computer aided design has been in use for some time. In 1976 the BEKAPAIBB platform of Total Oil (Indonesia) Ltd was installed off the Malaysian coast. Its certification, prior to its installation, was based on a structural model developed through interactive graphics [48].

IV. TURNKEY SYSTEMS

The size of a computer aided design system is not dependent on application of design alone. Application software requires a certain minimum amount of computational power and memory. The hardware minutirarization and the progress in software engineering is constantly increasing the potential of smaller computers to be utilized in areas which were once the realm of the larger mini and maxi computers. Velez-Jahn reported his experience at the 1979 International Conference on the Application of Computers in Architecture, Building Design and Urban Planning [49] with two different types of microcomputers, the TRS-80 and the Tektronix T-4051. Utilizing boolean graphic representation of building elevations at the early stages of architectural design.

The implementation of a full computer aided design system with a microcomputer, however, is still not feasible. This is especially true as the present demand for more applications, interdisciplinary design capabilities and other software tools increases, requiring ever greater computational and memory capacity from the present available systems.

A typical feature of any computer aided design system is its need for a wide range of software tools. These tools may range from very basic data handling routines to packages of mathematical procedures, graphics packages, design rule access systems to fully integrated systems. The common problem of computer aided design systems is that even if such software tools are available, it is a major task to put them together into a satisfactory or even a merely operational system. It is largely for this reason the integrated turnkey systems have been by far the most popular since they appeared on the market in early 1970.

These systems have been designed to incorporate the available tools into an acceptable operational system. Having one source provide the support for both hardware and software is very attractive. The user does not have to deal with a multiplicity of vendors to assure proper support for his system. This becomes very important as new application software is developed by the vendors, the user can be assured of compatibility with his system.

The typical turnkey system consists of a graphic input station (digitizer, tablet, function key, joystick or keyboard), an output station (flatbed, drum, light beam, microfilm or electrostatic plotter), an interactive crt work

station, a large secondary mass memory (disc, tape or drum) for storing large data bases, the minicomputer and, in some cases, a communications interface to a remote processor. The software consists of both systems and applications capabilities for at least two, and sometimes three dimensional, graphic data bases. By 1975 there were about 500 such systems in operation, with almost one half having been sold in that same year [50]. By the end of 1979, the U. S. based manufacturers alone had installed 2,992 systems throughout the world [51], and by the middle of 1981 this figure surpassed 5700 systems delivered [52].

Prior to 1979 the bulk of the computer aided design systems produced by the turnkey vendors were absorbed by the mechanical design and electrical segments of the market, specifically by the aerospace and automotive industries for the design and manufacture of discrete products, and the electronics industry for integrated circuit design and printed circuit board layout. Figure 13 includes the primary applications of turnkey systems in 1975 as developed by their major producers. In 1975, 75 percent of the market was shared amongst three of the vendors listed, Applicon, CALMA and Computervision [53].

Vendor	Applicon	Auto-Trol	CALMA	Computervision
1st Delivery	1970	1973	1971	1969-1970
Primary Applications	IC & PC	D & PC	IC & PC	IC, PC & D
Primary Input & Edit Devices	Digitizer	Digitizer keyboard/ display	Digitizer keyboard/ display	Digitizer/ plotter
	Tablitizer w/optional plotter	Interactive crt with cursor	CRT with tablet and keyboard	CRT with tablet and keyboard
	CRT with tablet and keyboard	Teletype ASR 33	Teletype ASR 33	Teletype ASR 33
	Magnetic tape	Magnetic tape	Magnetic tape	Magnetic tape
Processor	PDP-11/05	Virian 620L/200	Nova 1220	Nova
Typical System Cost	122,000	126,895	131,000	110,000

NOTE: IC = Integrated Circuits
PC = Printed Circuits
D = Drafting

Fig. 13: 1975 Typical Computer Aided Design Turnkey Systems

By 1979 the computer aided design market was being led by Applicon, Auto-Trol, CALMA and Computervision. In 1979, the application mix shifted toward the areas of architecture and engineering, mapping, and petrochemical. The architecture and engineering installed base increased by 73 percent, while the more traditional mechanical design and electrical application areas increased by 37 and 53 percent respectively [54]. The most common systems supplied during

this period was in support of drafting and mapping functions. The total market grew from 36.5 to 322 million dollars for U. S. manufacturers in 1979, expecting to reach 695 million dollars for calendar year 1981. A more impressive statistic is the growth in the percent of vendor revenues in the architecture and engineering arena from .03 percent in 1975 to 16 percent in 1979.

Figure 14 represents the 1981 view of the information presented for 1975 in figure 13 [55]. When comparing figures 13 and 14 one can observe the growth of the architecture and engineering market's corresponding effect on the development of the turnkey vendors' application environment.

The wide possibility of applications to be implemented into a system coupled with the difficulty of that implementation and the complexity of system configurations are natural enforcers of specialization amongst the various turnkey vendors. In fact, if one reviews the market shares of the 1979 turnkey system leaders one can readily observe this phenomenon. On a worldwide basis, Computervision was the revenue leader and also had over 40 percent of the mechanical application area. Looking at the U. S. installed base, however, Applicon had the largest number of systems

installed. CALMA was the leader in electrical application, while Auto-Trol was the major supplier of the petrochemical business [56].

Vendor	Applicon	Auto-Trol	CALMA	Computervision
Target Application Environment	CAD & drafting	Drafting, AE	IC, PC, MD, MD, D, AEC & mapping	MC, D, NC, PC, IC, electrical, cartography, plant & piping, structural
Primary Input & Edit Devices	Digitizer tablets	Optec digitizer	Large digitizer	CVD digitizers
	B/W or color displays	19", 25" CC-80 storage/ refresh terminals	Choice of 3 high-resolution raster displays	Raster display
	Plotters	Variety of plotters options	Range of plotter	Electro-static or drum plott.
	Alpha terminals	Alpha terminal	Vector memory display (VMD) for IC appl.	Disk storage
Processor	Graphics 32 plus PDP-11 CPU, 30-200Mb disk	Univac V77 or DEC VAX CPU, 80-300Mb disk	Eclipse S230 CPU, 300Mb disk	Computer-vision CGP-100/ 200 CPU
Typical System Cost	250K-350K	150K+	200K-300K	150K-500K

NOTE: IC = Integrated Circuits; NC = Numerical Control; PC = Printed Circuits; MD = Mechanical Design; DM = Drafting & Manufacturing; D = Drafting; AEC = Architect, Engineering & Construction.

Fig. 14: 1981 Typical Computer Aided Design Turnkey Systems

Even though a majority of the turnkey systems are configured for a specific applications environment, many vendors would define their systems as sufficiently generic to be applicable to other environments as well [57]. It is this vendor's approach to the computer aided design market in general which causes difficulties in identifying a leader, or group of leader vendors for the developing architecture and engineering market.

Waltz identified the vendors who address the architecture and civil engineering application area most specifically as M & S Computing, Synercom, CALMA, Cal Comp and Comarc [58], but offers no supporting evidence. Reviewing the vendor's product description literature does not clarify the situation, it only gives a rather weak indication of vendor's preferred application environment while attempting to retain a generic application profile. The situation becomes even more confused since most vendors with application packages in the architecture and engineering area also have well established market positions in their respective primary application area and desire to retain a sufficiently strong tie to that identity so as not to imperil their market position.

Each of the four vendcrs represented in figure 14 have developed their system configuraticn and application software sufficiently to compete in the architecture and engineering market. Three dimensional geometric descripticn, piping isometric, structural design, etc., have all benn implemented, with other application packages under development, such as pre-stressed concrete and steel detailing. Althcugh additional analysis and design packages are in demand, Kelly reported user's growing concern and desire for better human engineering [59]. The human machine interface will need to be improved to ensure acceptance of the computer as his new design partner by the growing number of users whc lack computer expertise.

Interest in distributed intelligence and communication will require an in depth review of the data management question. The problem will be to accept deterioraticn of response time or hardware upgrading as compromise, either way cost will be a major factor.

V. CONCLUSIONS

There is not yet an architecture and engineering computer aided design system available. The turnkey vendors have provided the architectural and engineering community with operational systems which are of usable quality. The interdisciplinary communications, the application oriented type of operation and distributed intelligence processing are typical characteristics of an architectural and engineering entity to which the computer aided design industry must become more responsive if it is to continue to grow in acceptance. The turnkey units which have been delivered in the architectural and engineering arena are being mostly utilized as drafting machines [60]. The architectural and engineering firms have come to realize the potential benefits which could be derived from a computer aided system not in its present utilization of producing drawings, but as a partner with the designer in the design process.

This new emphasis is on man-machine interaction rather than on man or machine action alone. The system which suggests itself from the view discussed in design theory is one which allows a man-machine coupling, joining the

capabilities of the designer and the computer, taking care to have nothing done by one of the two if the other can do it better. Thus the man is given more freedom to be creative while the machine does more routine analysis and technical review of design. A balance between the user and the computer must be found to assure the survival of the design activity itself as a creative force. There is the danger of subjugating the qualitative element of design activity to the quantitative one, especially as more and more application packages are demanded by users and developed by the vendors without an overall plan of the final total system configuration. A senior partner approach where man has the final determination of the action to be taken while the computer becomes more of a "technical" assistant, might be a solution to the problem. The proper implementation approach would assure no alienation or loss of job satisfaction need be experienced by the architect and engineer.

The turnkey industry appears to have been responsive to the needs of the architects and engineers recently. There are more application packages available in the market today than five years ago and more being developed for future applications. The question remains on how the industry will

approach the problem of incorporating distributed processing, interdisciplinary design requirements and the management of the data base. This may well become a very pressing question in the near future.

Computer aided design touches upon many other areas not discussed. These offer opportunities for further research and investigation, such as the question of adopting standards for the computer aided design industry. Sweet discusses the problem when certain features of systems are of a proprietary nature and, therefore, not standardizable. The Xerox Corporation has forced vendors to comply with Xerox standards to avoid becoming a single product consumer due to lack of portability of the products of other potential suppliers.

The requirement for certification of structures, e.g. oil drilling platforms, and professional responsibility for the soundness of design, e.g. the degree of responsibility of failure or collapse, have new implications for the computer aided design projects. The use of computers and computer programs in no way alters the normal professional responsibility of the architect and engineer. However, in using such sophisticated tools, he should have some guidelines and standards in order to assess the program's

reliability and suitability for his particular problem. Except for the very simplest of programs, it is not feasible for the architect and engineer thoroughly to check its operation. Proper software documentation can be of great assistance, but may not be, by itself sufficient to satisfy the moral and legalistic obligation of the professional designer.

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